

An Enhanced Inherited Crossover GA for the Reliability Constrained UC Problem

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Abstract—This paper solves reliability constrained unit commitment problem (UCP) for a composite power system network using network equivalent technique. Here, the integration of generation and transmission system reliability forms a composite power system model. The inclusion of load forecast uncertainty for the solution of unit commitment problem will give more accurate assessment of spinning reserve (SR). Probabilistic techniques help in setting the reserve requirement which is defined by reliability indices such as loss of load probability (LOLP) and expected energy not supplied (EENS). Reliability network equivalent techniques represent each market player in a power market. The unit commitment problem is solved by a genetic algorithm (GA) resulting in near-optimal unit commitment solutions and the required spinning reserve capacity is effectively scheduled according to the desired reliability level. The proposed enhanced inherited crossover operation in GA will inherit more information from the parent chromosomes thereby it improves the convergence fact and quality of solution. The effectiveness of the proposed technique for UCP is validated on IEEE RTS 24 bus system and a South Indian (Tamilnadu) 86 bus system.

Index Terms— Composite generation and transmission system, Genetic algorithm, Load forecast uncertainty, Network equivalent technique, Probabilistic techniques, Unit commitment problem.

NOMENCLATURE

B_j An outage condition of transmission network.
 $C_{st,i}$ Total start- up cost of unit i during at k^{th} hour.
 D_k Total system demand at k^{th} hour.
 $DR(i)$ Ramp down rate limit of unit i.
 $EENS_k^g$ EENS due to generation outage
 $EENS_{b,k}$ EENS at each BLP at k^{th} hour.
 $EENS_k^t$ EENS due to transmission outage
 $EENS_k^c$ Composite System EENS at k^{th} hour.
 $EENS_k^c(s)$ Composite System EENS for the load step s of k^{th} hour.
 $EENS_{cal,k}$ System reliability index EENS at k^{th} hour.
 $F(B_j)$ Frequency of occurrence of outage B_j
 $F_i(P_{i,k})$ Fuel cost function i.e. $F_i(P_{i,k})=a+b*P_{i,k}+c*P_{i,k}^2$

a, b and c are generator cost coefficients
 $I_{i,k}$ Status of unit 'i' at k^{th} hour k
H Dispatch period in hours.
 L_i Load curtailed due to generator contingency i.
LC Total number of contingencies leading to load curtailment.
 L_{bj} Load curtailed at BLP 'b' due to transmission line contingency j.
 $LOLP_k^g$ LOLP due to generation outage.
 $LOLP_{b,k}$ LOLP at each BLP 'b' at k^{th} hour.
 $LOLP_k^t$ LOLP due to transmission outage.
 $LOLP_k^c$ Composite System LOLP at k^{th} hour
 $LOLP_k^c(s)$ Composite System LOLP for the load step s
 $LOLP_{cal,k}$ System LOLP at k^{th} hour.
 p_i State probability for state i.
 $P_{i,k}$ Generation power output of unit i at k^{th} hour.
 $P_{i,min}$ Minimum power output of unit i.
 $P_{i,max}$ Maximum power output of unit i.
 P_{bf-bt} Power flow between bus bf and bt.
 $P_{bf-bt,max}$ Maximum power flow limit between bus bf-bt.
 P_{cj} Probability of load that exceed the maximum load that can be supplied without failure
 $P(B_j)$ Probability of existence of outage B_j
 $PL(s)$ Probability of load step s.
 SR_k System spinning reserve at k^{th} hour.
 $T^{on}(i)$ Minimum On time for unit i.
 $T^{off}(i)$ Minimum Off time for unit i.
 $UR(i)$ Ramp up rate limit of unit i.
 $V_{p,min}, V_{p,max}$ Minimum/Minimum limit of voltage at bus p.
 V_p Voltage at bus p.
 $X^{on}(i, k)$ Time duration for which unit i is On at time k.
 $X^{off}(i, k)$ Time duration for which unit i is Off at time k.

I. INTRODUCTION

Unit commitment (UC) plays a major role in the daily operation planning of power systems. System operators need to perform many UC studies, in order to economically assess the spinning reserve capacity required to operate the system as securely as possible. The objective of the UC problem is the minimization of the total operating cost of the generating units during the scheduling horizon, subject to system and unit constraints. The solution of the above problem is a very complicated procedure, since it implies the simultaneous solution of two sub problems: the mixed-integer nonlinear programming problem of determining the on/off state of the generating units for every hour of the dispatch period and the quadratic programming problem of dispatching the forecasted load among them. The evaluation of the system spinning reserve is usually based on deterministic criteria. According to the most common deterministic criteria, the reserve should be at least equal to the capacity of the largest unit, or to a specific percentage of the hourly system load. The basic disadvantage of the deterministic approach is that it does not reflect the stochastic nature of the system components. On the contrary, the probabilistic methods [1]–[4] can provide a more realistic evaluation of the reserve requirements by incorporating various system uncertainties, such as the availability of the generating units, the outages of the transmission system, and the load forecast uncertainty. These methods combine deterministic criteria with probabilistic indexes, in order to find a UC solution that provides an acceptable level of reliability.

Most of the existing probabilistic methods [2]–[4], are based on the priority list (PL) method in order to solve the UC problem. The PL method is very simple and fast, but it results in suboptimal solutions. Dynamic programming (DP) [1] and Lagrangian relaxation (LR) [5] have also been used for the solution of the UC problem. The main disadvantage of DP is that it suffers from the “curse of dimensionality,” i.e., the computational requirements grow rapidly with the system size. The Lagrangian relaxation method provides a fast solution but it may suffer from numerical convergence and solution quality problems. Aside from the above methods, there is another class of numerical techniques applied to UC problem. Specifically, there are artificial Neural Network, simulated annealing (SA), and GA. These methods can accommodate more complicated constraints and are claimed to have better solution quality. SA is a powerful, general-purpose stochastic optimization technique, which can theoretically converge asymptotically to a global optimum solution with probability 1. One main drawback, however, of SA is that it takes much CPU time to find the near-global minimum. GA is a global optimization method which works well and efficiently on objective functions which are complex in terms of the nonlinearities and constraints imposed. One of the disadvantages of GA is premature convergence, because when the selection is based on the quality of the individual, the genetic information of the best individuals tends to dominate the genetic characteristics of the

population [6]. To avoid disadvantages of this type in UCP, in this paper, the use of a GA is proposed, which is based on an enhanced inherited crossover operation. Thereby, the exchange of genetic information between two individuals with the modified crossover operator is more and improves the quality of solution.

The network equivalent technique is used to by integrate unavailability of generating units/transmission lines and load forecast uncertainty for the solution UCP. The generation system in the market is represented by an equivalent multistate generation provider (EMGP) and with an equivalent assisting unit approach [7] where reliability of generation system is calculated. Using the network equivalent technique, the transmission system is modeled [8] and inclusion of transmission system reliability is employed by computing the transmission line outage at each load point using conditional probability approach [7-8]. Then composite system LOLP and EENS can be estimated by adding the individual LOLP and EENS caused by generating system/transmission system, respectively. The above reliability parameters are taken into account in order to provide a more realistic evaluation of the system reserve requirement.

II. UC PROBLEM FORMULATION

In this section, UCP is formulated by incorporating reliability constraints.

A. Objective function

The objective of the UCP is the minimization of the total operating cost of the generating units during the scheduling horizon. For N generators, the operation cost (OC) is defined mathematically as given in equation (1).

$$\min OC = \sum_{k=1}^H \sum_{i=1}^N F_i(P_{i,k}) * I_{i,k} + \sum_{i=1}^N C_{st,i} \quad (1)$$

B. Constraints

The minimization of the objective function is subject to a number of system and unit constraints, as follows.

1. Power balance constraints

The total generated power at each hour must be equal to the load of the corresponding hour. This constraint is given by

$$\sum_{i=1}^N P_{i,k} * I_{i,k} = D_k, k \in [1, H] \quad (2)$$

2. Spinning reserve constraints:

$$\sum_{i=1}^N P_{i,\max} * I_{i,k} \geq D_k + SR_k, k \in [1, H] \quad (3)$$

3. Capacity limits of generating unit

$$P_{i,\min} \leq P_{i,k} \leq P_{i,\max} \quad (4)$$

4. Unit minimum ON/OFF durations

$$[X^{on}(i,k) - T^{on}(i)] * [I_{i,k-1} - I_{i,k}] \geq 0 \quad (5)$$

$$[X^{off}(i,k-1) - T^{off}(i)] * [I_{i,k-1} - I_{i,k}] \geq 0 \quad (6)$$

5. Unit ramp constraints

$$P_{i,k} - P_{i,k-1} \leq UR(i) \quad (7)$$

$$P_{i,k-1} - P_{i,k} \leq DR(i) \quad (8)$$

6. Networks constraints

a. Voltage magnitude constraints

$$V_{p,\min} \leq V_p \leq V_{p,\max} \quad (9)$$

b. Line flow constraints

$$|P_{bf-bt}| \leq P_{bf-bt,\max}, \quad bf-bt \in NB \quad (10)$$

7. Reliability constraints

Spinning reserve requirements in equation (3) can be calculated using either deterministic criteria or probabilistic techniques. However, in the proposed technique probabilistic reserve assessment with spinning reserve requirements are assessed according to the desired level of reliability specified for the composite generation and transmission network. Therefore spinning reserve requirement should satisfy the reliability constraints given as follows:

$$LOLP_k \leq LOLP_{spec} \quad k \in [1, H] \quad (11)$$

$$EENS_k \leq EENS_{spec} \quad k \in [1, H] \quad (12)$$

III. RELIABILITY MODELLING

A. Modeling of Generating systems

For the purpose of reliability analysis, each generating unit is represented by the two-state model [7], according to which a unit is either available or unavailable for generation. In [7], the notion of unavailability is referred to as the steady state outage replacement rate or, more commonly, as the forced outage rate. Consider a power system with 'T' Generating system (GS) and therefore 'T' EMGPs. Let 'm' be the number of BLPs. Each of the EMGP is connected to different BLPs through the transmission system. The capacity outage probability table (COPT) of an EMGP can be realized by an available capacity probability table (ACPT) [8]. The parameters of an ACPT are the state available generation capacity AG_j , state probability p_j and frequency f_j . All EMGP_j ($j=1, \dots, h-1, h+1, \dots, Y$) are added one by one as new unit to generate Total system available capacity probability table (TSACPT).

Calculation of Reliability indices

The system reliability indices for generation outages are calculated at hour 'k' using the equations given below.

$$LOLP_k^g = \sum_{i=LC} p_i, \quad k \in [1, H] \quad (13)$$

$$EENS_k^g = \sum_{i=LC} p_i L_i, \quad k \in [1, H] \quad (\text{MWh}) \quad (14)$$

A reduction in the time requirements of the proposed method can be achieved by omitting the outage levels for which the cumulative probabilities are less than a predefined limit [8], e.g., 10^{-7}

B. Modeling of Transmission systems

Electrical energy is delivered from an EMGP to its Bulk

load points (BLPs) through the transmission network. Failures of transmission network components can affect the capacity that can be transferred from an EMGP to its BLPs. In the composite power system, it is virtually impossible to provide the same level of service reliability to every customer. There are two basic types of transmission failures which affect reliability level of transmission system at each BLPs. The first type of failure is caused due to the isolation between BLPs and EMGP. In this case, only the isolated bulk load points are affected and energy delivered at that BLP is 0. The second type of failure is due to the line flow constraint violations such as congestion. In this case, ac power flow has to be analyzed to determine network violations for each area. If there are no network violations, the energy that can be delivered at the BLPs can be up to their peak loads. If network violations exist, the loads for all of the BLPs have to be shed proportionally (due to equality transmission right) to release the network violations (corrective action) and the energy delivered for an isolated BLP will be its peak load minus the load shed [8]. Network equivalent for each transmission network for the corresponding BLP and EMGPs are shown in Fig 1. Equivalent multi-state transmission provider (EMTP) between EMGPs and BLPs is represented as EMTPs. Hence the total transmission system reliability is the average of the individual transmission reliability (EMTP) at each of the BLPs.

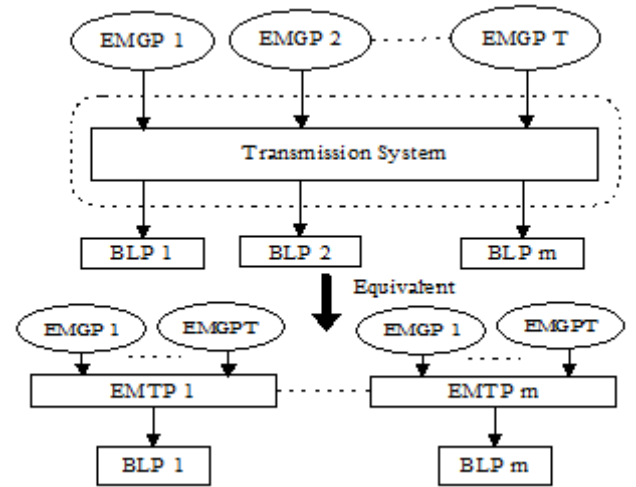


Fig. 1. Transmission system and EMGP

Calculation of Reliability indices

The conditional probability approach [7] is applied to these equivalent transmission models and reliability indices at each of the BLPs are calculated using equations (15)-(16).

$$LOLP_{b,k} = \sum_{j=no. of states} [P(B_j) * P_{cj}], \quad b \in [1, m] \quad (15)$$

$$EENS_{b,k} = \sum_{j=no. of states} [P(B_j) * P_{cj} * L_{bj}], \quad b \in [1, m] \quad (\text{MWh}) \quad (16)$$

System reliability indices due to transmission unavailability are calculated using following equations

$$LOLP_k^t = \max \left(\sum_{b=1}^m LOLP_{b,k} \right) \quad k \in [1, H] \quad (17)$$

$$EENS_k^t = \sum_{b=1}^m (EENS_{b,k}^t), \quad k \in [1, H] \text{ (MWh)} \quad (18)$$

In this approach, only the single line outage is taken into account and the only assumption that is made during the calculation is that adequate generation is available and therefore loss of load at any of the BLPs is due to transmission unavailability (EMTP) between the corresponding EMGPs and BLP.

C. Modeling of Composite system

Composite system reliability index is calculated by adding the generation and transmission system reliability indices using equation (19)-(20).

$$LOLP^c_b = LOLP^g_b + LOLP^t_b \quad (19)$$

$$EENS^c_b = EENS^g_b + EENS^t_b \quad (20)$$

D. Load Forecast Uncertainty model

The short-term forecast of the load demand is a problem with forecast uncertainties that plays a major role in the solution of the UCP. The load forecast uncertainty is represented by a normal distribution curve in which the mean value is the forecasted peak load. The normal distribution curve is divided into a discrete number of intervals and the load in the midpoint of each interval represents the probability for that interval. To simplify the calculation, a seven-step distribution ($0, \pm 1\sigma, \pm 2\sigma, \pm 3\sigma$) is often used where, standard deviation, is 2-5% of the expected load [7]. Such a model will encompass more than 99% of load uncertainty. Based on the above analysis, the LOLP and EENS indices for each hour can be calculated by the following equations:

$$LOLP_{cal,k} = \sum_{s=1}^7 LOLP^c_k(s) * PL(s), \quad k \in [1, H] \quad (21)$$

$$EENS_{cal,k} = \sum_{s=1}^7 EENS^c_k(s) * PL(s), \quad k \in [1, H] \text{ (MWh)} \quad (22)$$

IV. OVERVIEW OF GENETIC ALGORITHM

GA is general purpose optimization algorithm based on the mechanics of natural selection and genetics. They operate on string structures (chromosomes), typically a concatenated list of binary digits representing a coding of the control parameters (phenotype) of a given problem. Chromosomes themselves are composed of genes. The criterion which evaluates the quality of each chromosome is given by the Fitness corresponding to the evaluation of each individual for the objective function. Once the fitness of each of the individuals in the population is known, it is subjected to a Selection process in which the best evaluated individuals have a greater probability of being chosen as Parents for the exchange of genetic information called Crossover. Then a percentage of the Offsprings (individuals generated in the crossover) are subjected to the Mutation process in which a random change is generated in the chromosome. This mutation process provides greater diversity between the individuals in the popu

lation. When the crossover and mutation processes are complete a new population is generated which replaces the original population. This must be repeated until one of the convergence criteria defined for the problem is met. Each of these cycles is known as a Generation.

A. Enhanced Inherited Crossover operation

Crossover is an extremely important operator for the GA. It is responsible for the structure recombination (information exchange between mating chromosomes) and the convergence seed of the GA and is usually applied with high probability (0.6–0.9). The chromosomes of the two parents selected are combined to form new chromosomes that inherit segments of information stored in parent chromosomes.

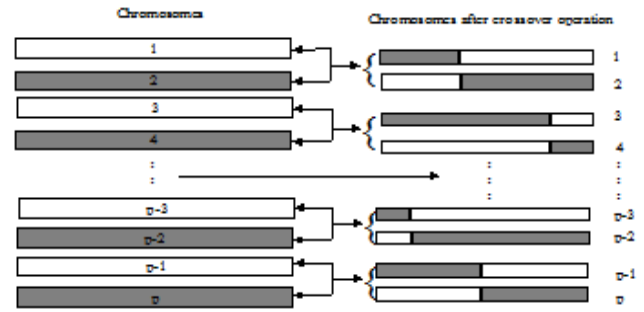


Fig.2 Traditional crossover operation

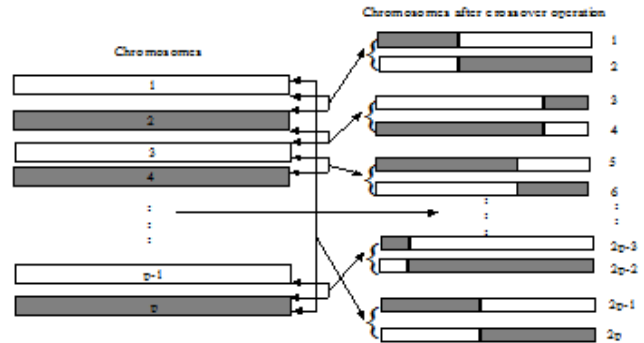


Fig. 3 Enhanced inherited crossover operation

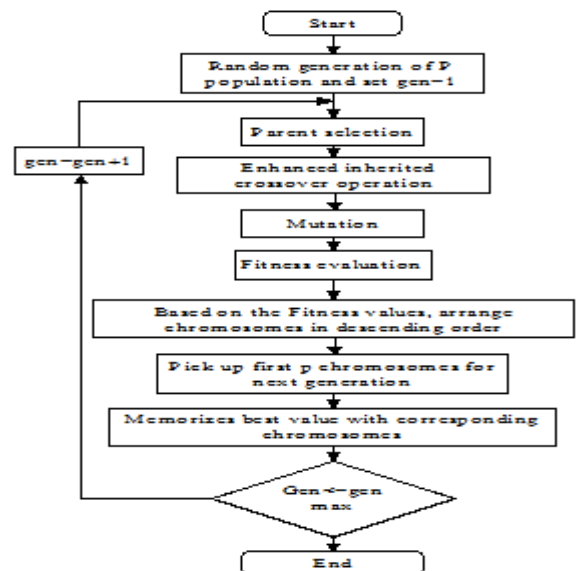


Fig.4 Flowchart for proposed enhanced inherited GA

Traditionally, in GA a linear crossover is performed on the two chromosome represented as a string, as shown in Fig.2. Here a chromosome 1 is combined with chromosome 2 of randomly selected chromosomes and two new chromosomes are formed from the information stored in parent chromosomes. Similar new chromosomes are formed between 3 and 4 and so on. Here chance of inheriting information from parent chromosomes is less, since there may be chance to inherit more information while combining the chromosomes 2 and 3 instead of chromosomes 1 and 2. In order to avoid this disadvantage, an enhanced inherited crossover operation is carried to transfer more information from parent to chromosomes.

Fig.3 clearly shows the enhanced inherited crossover operation. At the end of the enhanced crossover operation, the number of population in GA is doubled, thereby the proposed enhanced inherited crossover operation inheriting more operation from the parent chromosomes. Then a percentage of the offspring (individuals generated in the crossover) are subjected to the Mutation process in which a random change is generated in the chromosome. This mutation process is carried for 2p size population and provides greater diversity between the individuals in the population when compared to simple genetic algorithm. When the crossover and mutation processes are complete, for new 2p size population, the fitness is evaluated for each individual for the objective function. Once the fitness of each of the individuals in the population is evaluated, then individuals are arranged in descending based on the fitness values. Then first p population is picked up for the next

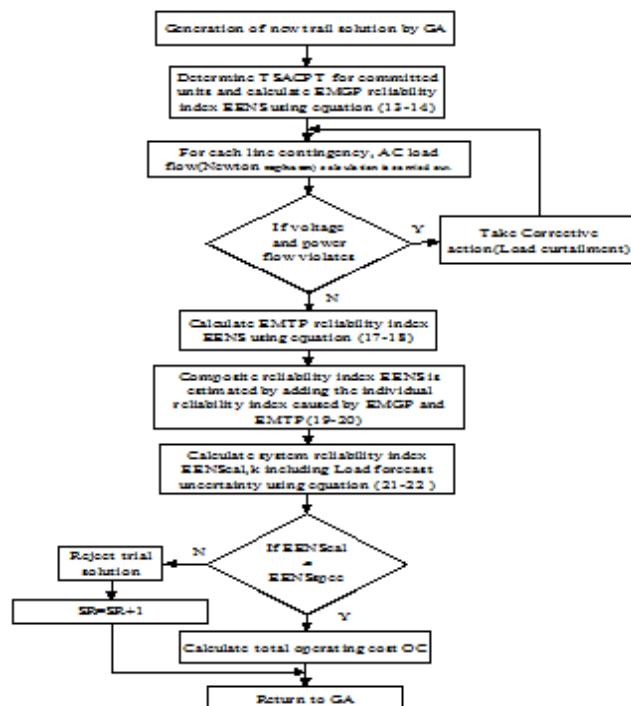


Fig. 5 Flowchart of the proposed reliability constrained UCP generation and process is repeated until it termination criteria is met. Here p is a population size. The flow of algorithm is shown in Fig. 4

V. SOLUTION METHODOLOGY

The flowchart of the proposed reliability constrained UCP using proposed GA is shown in Fig. 5.

VI. NUMERICAL RESULTS

Simulations are carried out on an IEEE RTS 24 bus system and a South Indian 86 bus system. All simulations are performed using a PC with Pentium(R) 3.40 GHz, 1GB RAM system on the MATLAB 7 environment. Three different strategies have been carried out to schedule the system spinning reserve and are given as follows:

Strategy 1: Calculation of required spinning reserve by deterministic approach.

Strategy 2: Calculation of required spinning reserve only with generation unavailability.

Strategy 3: Calculation of required spinning reserve by considering generation / transmission unavailability and load forecast uncertainty.

A. IEEE RTS 24 bus system

The proposed method has been applied to IEEE RTS 24 bus system which is also called as Roy Billinton test system (RBTS) and is given in [9]. The generation cost coefficient is adapted from [9]. Generation/transmission line reliability data are taken from [10] and load data is adapted from [11].

Strategy 1:

In this section, unit commitment problem is solved using proposed GA algorithm and results are compared with [11-13]. Here the system spinning reserve is deterministically set to the maximum capacity of the largest committed unit as in the ref [11-13]. For the sake of comparison with [11-13], network constraints and reliability constraints are not included. Here UC problem is solved using the proposed GA and lambda-iteration technique is used to solve the economic dispatch problem.

Table 1 gives the comparison of the minimum total operating cost obtained by GA with respect to other techniques reported in the literature. It is clearly seen that the proposed method yields better results than other technique so far proposed in the literature. The minimum cost so far reported in literature is \$ 721352.9 [13] which is \$ 25.68 higher than that obtained from proposed GA. Also the proposed GA yields the better solution with the introduction of enhanced inherited crossover operation in GA. The UC status for case 1 is given in Table 2.

In this section, reliability constraints are included along with all constraints. Here reliability constrained UC problem is solved using the proposed GA and ED problem is solved using conventional method.

TABLE 1 COMPARISON OF RESULTS-STRATEGY 1

Solution Techniques	Minimum value (\$)
ANN-DP[11]	729326.5
ILR[12]	725996.9
IPL-ALH [13]	721352.9
Simple GA	727165.41
Enhanced Inherited crossover GA	721327.21

TABLE II. UC SCHEDULE- STRATEGY 1

Hour	Unit Status 1,2,...,26	Load	Fuel cost \$	St. cost
1	11111111111000000000000000	1700	19015	106.93
2	11111111111000000000000000	1730	19371	0
3	11111111111010000000000000	1690	18789	0
4	1111111111101000000100000000	1700	18966	0
5	11111111111000000000000000	1750	19610	74.329
6	11111111111100000000000000	1850	21187	130.53
7	111111111111000100001000	2000	23805	172.02
8	111111111111110000000000	2430	32643	1048.3
9	111111111111110000000000	2540	34726	0
10	1111111111111111000000	2600	36050	0
11	1111111111111111101110	2670	38251	115.37
12	1111111111111111100000	2590	35816	0
13	1111111111111111100000	2590	35816	0
14	111111111111111000000000	2550	34917	0
15	111111111111111111110000	2620	36582	0
16	111111111111111111100110	2650	37606	74.587
17	11111111111111111000000000	2550	34917	0
18	11111111111111111000000000	2530	34534	0
19	11111111111111111000000000	2500	33963	0
20	11111111111111111000000000	2550	34917	0
21	111111111111111111000000	2600	36050	0
22	11111111111111111000000000	2480	33584	0
23	1111111111111100100110000	2200	27423	0
24	11111111111100000000000000	1840	21066	0
Total cost (\$) = 721327.21				

Strategy 2:

For sake of comparison with Ref. [14], loss of load probability (LOLP) index is used to set the level of spinning reserve. Also LOLP index is expressed in % and the lead time of the system is fixed for four hours. Also the network security constraints are not considered. Table 3 gives the comparison of the total operating cost obtained by proposed GA with respect to other techniques. The LOLP index is kept as 1.5 % for comparison.

It can be inferred from the results that the solution obtained from the proposed method is better than the SA and GA. The proposed enhanced inherited crossover GA finds a solution which is \$ 654 lesser for the LOLP_{spec} 1.5 % when compared with SA and is found to be promising. The UC status for each unit of the 26 unit system for LOLP_{spec} = 1.5 % is given in Table 4.

Strategy 3:

In this section, three different case studies have been carried out to understand the importance of inclusion transmission line outage and load forecast uncertainty.

Case 1: Calculation of required spinning reserve only with generation unavailability.

TABLE III. COMPARISON OF RESULTS- STRATEGY 2

Solution Technique	Total operating cost \$		
	Minimum value	Mean value	Maximum value
SA[14]	710696	710971	711315
Simple GA	710652	712014	713374
Modified GA	710042	710673	711088

TABLE IV. UC SCHEDULE- STRATEGY 2

Hour	Unit status 1,2,...,26	Load	Fuel Cost(\$)	St Cost
1	11111111100000000000000000	1700	18429	0
2	11111111100000000000000000	1730	18789	0
3	11111111100000000000000000	1690	18205	0
4	11111111101000000000000000	1700	18429	81.606
5	11111111101000000000000000	1750	19030	0
6	11111111110000000000000000	1850	20478	172.16
7	11111111111000000000000000	2000	22893	132.62
8	11111111111110000000000000	2430	32071	967.37
9	11111111111111000000000000	2540	34298	0
10	11111111111111100000000000	2600	35960	360.62
11	11111111111111110000000000	2670	37608	0
12	11111111111111111000000000	2590	35726	0
13	11111111111111111000000000	2590	35726	0
14	11111111111111101000000000	2550	34541	0
15	1111111111111110111110000	2620	36345	0
16	1111111111111110111111000	2650	37231	39.993
17	11111111111111101000000000	2550	34541	0
18	11111111111111100000000000	2530	34063	278.69
19	11111111111111100000000000	2500	33410	0
20	11111111111111100000000000	2550	34533	0
21	1111111111111110111000000	2600	35800	0
22	11111111111111100000000000	2480	33025	0
23	11111111111110000000000000	2200	26617	0
24	11111111110000000000000000	1840	20262	0
Total cost = 710042.64 \$				

TABLE V. COMPARISON OF DIFFERENT CASESTUDIES (LOAD =1700 MW)-STRATEGY 3

	No reserve	Deterministic Approach	Probabilistic Approach					
		10 % of Load as reserve	EENS _{spec} =3 MWh			EENS _{spec} =5 MWh		
			Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
Op. Cost (\$)	18221	18429	18449	18553	18659	18343	18449	18449
LOLP _{cal}	16.99	0.1847	0.1846893	0.1835631	0.124659	0.4600178	0.1846893	0.1846893
EENS _{cal} , MWh	127.6	2.993726	2.9934153	1.6193416	0.3924653	4.6154566	2.9934153	2.9934153
SR, MW	-	222	222	298	374	146	222	222
EENS _{spec} , MWh	-	-	3	3	3	5	5	5

TABLE VI. GENERATED POWER SCHEDULE (LOAD =1700 MW) - STRATEGY 3

Unit no.	No Reserve	10 % of load as SR		EENS _{spec} =3 MWh						EENS _{spec} =5 MWh					
				Case 1		Case 2		Case 3		Case 1		Case 2		Case 3	
		P _g	R _g	P _g	R _g	P _g	R _g	P _g	R _g	P _g	R _g	P _g	R _g	P _g	R _g
P1	400	400	0	400	0	400	0	400	0	400	0	400	0	400	0
P2	400	400	0	400	0	400	0	400	0	400	0	400	0	400	0
P3	350	350	0	350	0	349	1.27	342	7.92	350	0	350	0	350	0
P4	145	137	17.5	137	18.1	133	21.7	131	23.9	141	14.2	137	18.1	137	18.1
P5	140	132	22.7	132	23.2	128	26.7	126	28.9	136	19.4	132	23.2	132	23.2
P6	135	127	27.7	127	27.6	124	31.1	122	33.2	131	23.9	127	27.6	127	27.6
P7	130	123	32.5	124	31.4	120	34.8	118	36.9	127	27.7	124	31.4	124	31.4
P8	0	15.2	60.8	15.2	60.8	15.2	60.8	15.2	60.8	15.2	60.8	15.2	60.8	15.2	60.8
P9	0	0	0	15.2	60.8	15.2	60.8	15.2	60.8	0	0	15.2	60.8	15.2	60.8
P10	0	15.2	60.8	0	0	15.2	60.8	15.2	60.8	0	0	0	0	0	0
P11	0	0	0	0	0	0	0	15.2	60.8	0	0	0	0	0	0
P12-P26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Case 2: Calculation of required spinning reserve by considering both generation and transmission unavailability.
Case 3: Calculation of required spinning reserve by considering generation / transmission unavailability and load forecast uncertainty.

In this study, only the EENS criterion is used to set the level of spinning reserve. In power system operation such a criterion is more appropriate than LOLP since EENS accounts for both the probability of outages and corresponding average load lost. For a system load of 1700 MW, Table 5 compares the results using deterministic approach, with and without reserve and with two different EENS_{spec} limit values in the probabilistic approach. It is observed from Table 5 that the cost of operation is well correlated with calculated level of spinning reserve (SR) where, the spinning reserve (SR) is found to increase as the EENS criterion (EENS_{spec}) is restricted. That is the SR_{cal} in case 3 is 222 MW when EENS_{spec} is 5 MWh. Also SR_{cal} is increased to 374 MW when the EENS_{spec} is 3 MWh.

From Tables 5 and 6, it is observed that the cost and the number of committed units are increased when transmission reliability constraints and load forecast uncertainty are included. Table 6 clearly gives the generation and reserve dispatch for each unit. When EENS_{spec} is 3 MWh, an increase in cost of 104 \$/h is observed (Table 5) when moving from Case 1 to Case 2 due to increase in committed units (Table 6). Increase in cost signifies the importance of considering transmission line reliability issues for calculating spinning reserve requirement in power system model. Also when EENS_{spec} is 3 MWh, an increase in cost of 106 \$/h is observed (Table 5) when moving from Case 2 to Case 3 due to increase in committed units (Table 5). Therefore it is vital to include load forecast uncertainty when reliability issues are considered. It is to be noted (Table 5) that the EENS_{cal} is well within EENS_{spec} in the probabilistic approach for all the three case studies. When there is no spinning reserve constraint it is obvious that the system is more unreliable with a LOLP of 16.999 and EENS_{cal} of 127.6 MWh. In deterministic method, the spinning reserve is considered as 10 % of the load. When SR is 10 % of the load, the actual levels of LOLP is 0.1846 and EENS_{cal} is 2.99 MWh. It is interesting to compare the deterministic reserve case when EENS_{spec} is 5 MWh set for the probabilistic reserve case where both of them yield 222 MW spinning reserve. When EENS_{spec} is having different

values i.e 3 MWh and 5 MWh, the reliability level for probabilistic approach will be higher or lower when compared with deterministic approach. However, increase or decrease in the reliability indices values depends on the choice of EENS_{spec}. The choice of EENS_{spec} can be determined by probabilistic approach from the trade off between cost and reliability level which makes probabilistic approach advantages over deterministic approach.

The commitment schedule for Case 3 when EENS_{spec} is 3 MWh is given in Table 7. Fig. 6 illustrates the variation of the available spinning reserve capacity over the scheduled period of 24 hours for the EENS_{spec} is 3 MWh and 5 MWh. Obviously the 3 MWh requires more spinning reserve when compared to 5 MWh. The total operating cost for various values of EENS_{spec} limits are shown in Table 8. Here the total operating cost of the system increases as EENS criterion is restricted.

TABLE VII. GENERATED POWER SCHEDULE (24 HOUR) - STRATEGY 3-CASE 3

Hour	Unit no. 1,2,...,26	Load	Fuel Cost \$	St. cost \$
1	111111111100000000000000000000	1700	18534	0
2	111111111100000000000000000000	1730	18893	0
3	111111111100000000000000000000	1690	18415	0
4	111111111100000000000000000000	1700	18534	0
5	111111111100000000000000000000	1750	19133	0
6	111111111110000000000000000000	1850	20817	221.08
7	111111111110000000000000000000	2000	23214	132.62
8	111111111111000000000000000000	2430	32071	833.12
9	111111111111100000000000000000	2540	34298	0
10	111111111111110000000000000000	2600	35960	360.62
11	111111111111011100000000000000	2670	37889	0
12	111111111111011100000000000000	2590	35992	0
13	111111111111100000000000000000	2590	35726	97.543
14	111111111111101000000000000000	2550	34541	0
15	111111111111101111000000000000	2620	36315	0
16	111111111111101111110000000000	2650	37231	39.993
17	111111111111101000000000000000	2550	34541	0
18	111111111111110000000000000000	2530	34063	278.69
19	111111111111100000000000000000	2500	33410	0
20	111111111111100000000000000000	2550	34533	0
21	111111111111110100000000000000	2600	35770	0
22	111111111111100000000000000000	2480	33025	0
23	111111111111010000000000000000	2200	26983	0
24	111111111111000000000000000000	1840	20695	0
Total operating cost = 712546.66				

B. South Indian (Tamilnadu) 86 bus system

The proposed model is validated on South Indian TamilNadu 86 bus system. The generation data and network data is taken from [15-16] and the reliability data of generation and transmission system are taken from [17-18]. Due to page limitation data's are not included in this paper. The single line

diagram of a South Indian 86 bus system is given in Appendix A. The generating system is divided into four independent generating companies EMGP (1 to 4). Using the network equivalent technique, the generation and transmission network is modeled and the simulation results for the various values of $EENS_{spec}$ limits are given in Table 9. It is noted that the spinning reserve required at each hour is increased or decreased in proportion to the specified reliability level. The commitment schedule for Case 3 when $EENS_{spec}$ is 50 MWh is given in Table 10.

TABLE VIII. TOTAL OPERATING COST

	$EENS_{spec}=3$ MWh	$EENS_{spec}=5$ MWh
	Case 3	Case 3
Cost(\$/day)	712544.45	709922.93

TABLE X. DISPATCH SCHEDULES FOR CASE 3 ($EENS_{spec}=50$ MWh)

Hour	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	SR	Load
1	173	173	173	173	173	130	130	130	130	105	105	105	0	0	0	0	0	505	1700
2	153	153	153	153	153	114	105	105	105	178	178	178	0	0	0	0	0	475	1730
3	159	159	159	159	159	118	0	0	0	184	184	184	55	55	55	30	30	425	1690
4	139	139	139	139	139	104	0	0	0	161	161	161	98.8	98.8	98.8	60	60	640	1700
5	156	156	156	156	156	116	105	105	105	105	105	105	55	55	55	30	30	365	1750
6	175	175	175	175	175	131	131	131	131	0	0	0	110	110	110	60	60	490	1850
7	183	183	183	183	183	137	137	137	137	105	105	105	55	55	55	30	30	430	2000
8	173	173	173	173	173	129	129	129	129	201	201	201	110	110	110	60	60	540	2430
9	183	183	183	183	183	137	137	137	137	210	210	210	110	110	110	60	60	430	2540
10	190	190	190	190	190	142	142	142	142	210	210	210	110	110	110	60	60	370	2600
11	199	199	199	199	199	149	149	149	149	210	210	210	110	110	110	60	60	300	2670
12	189	189	189	189	189	141	141	141	141	210	210	210	110	110	110	60	60	380	2590
13	189	189	189	189	189	141	141	141	141	210	210	210	110	110	110	60	60	380	2590
14	184	184	184	184	184	137	137	137	137	210	210	210	110	110	110	60	60	420	2550
15	193	193	193	193	193	144	144	144	144	210	210	210	110	110	110	60	60	350	2620
16	197	197	197	197	197	147	147	147	147	210	210	210	110	110	110	60	60	320	2650
17	203	203	203	203	203	152	152	152	152	210	210	210	110	110	110	60	60	270	2700
18	182	182	182	182	182	136	136	136	136	210	210	210	110	110	110	60	60	440	2530
19	179	179	179	179	179	133	133	133	133	208	208	208	110	110	110	60	60	470	2500
20	184	184	184	184	184	137	137	137	137	210	210	210	110	110	110	60	60	420	2550
21	190	190	190	190	190	142	142	142	142	210	210	210	110	110	110	60	60	370	2600
22	197	197	197	197	197	147	147	147	147	210	210	210	110	110	110	60	60	320	2650
23	172	172	172	172	172	128	128	128	128	200	200	200	55	55	55	30	30	545	2200
24	191	191	191	191	191	143	143	143	143	105	105	105	0	0	0	0	0	365	1840

It is obvious when the $EENS_{spec}$ is restricted from 50 MWh to 10 MWh the total operating cost is increased from 14870493 INR/day to 14946074 INR/day. (i.e). SR_{cal} is more when $EENS_{spec}$ is 10 MWh than 50 MWh.

VII. CONCLUSION

This paper proposed a composite power system network equivalent technique to get the solution for reliability constrained unit commitment schedule. The reliability indices such as LOLP and EENS are calculated using probabilistic

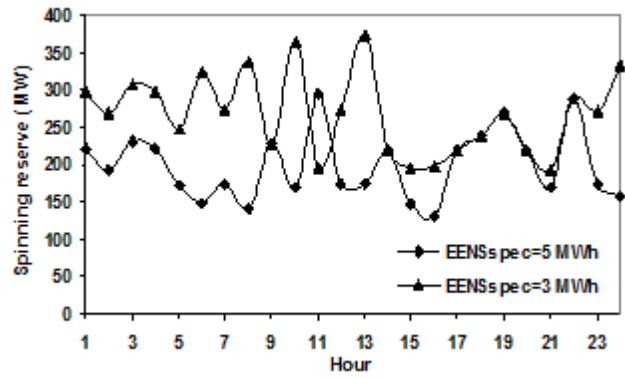
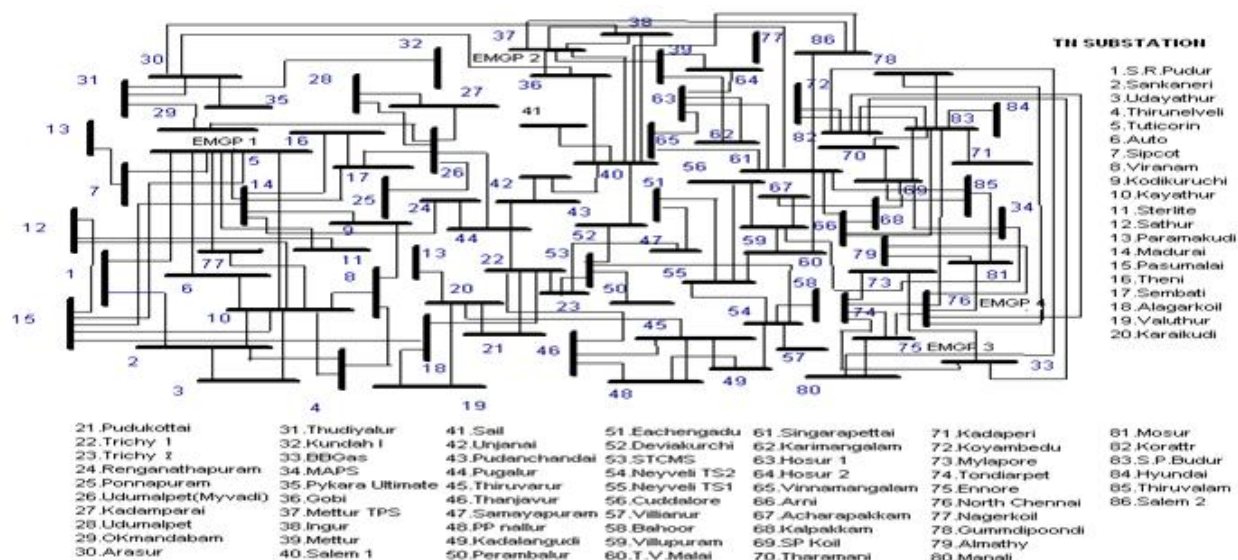
Fig: 6 Spinning reserve at each hour for different $EENS_{spec}$

TABLE IX. TOTAL OPERATING COST

	$EENS_{spec}=50$ MWh	$EENS_{spec}=10$ MWh
	Case 3	Case 3
Cost(INR/day)	14870493	14946074

approach for the composite power system model incorporating load forecast uncertainty. By incorporating transmission line outages and load forecast uncertainty an accurate estimate of spinning reserve requirement is obtained. The results found, when compared with those obtained by other GA, validate the application of enhanced inherited cross-over GA to the reliability constrained unit commitment problem. An improvement is observed in the convergence and in the quality of the best solution found. The proposed model is validated on IEEE RTS 24 bus and a South Indian Tamilnadu 86 bus system, thereby efficient commitment schedules are obtained for the forecasted load.

APPENDIX A



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